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Developing a Methodology for Performing Listening Tests Related to Building Acoustics

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CHAPTER 7 Developing a Methodology for Performing Listening Tests Related to Building Acoustics

7.1. Introduction

Human capacity to experience taste, smell, touch, colour of light, temperature, or colour of sound is quite remarkable and has been quite thoroughly investigated via perception tests in psychology and medicine with the aim of assessing the human ability to qualitatively and quantitatively discriminate between different levels of observables. Even in marketing, research perception tests are commonly used to determine individual or common trends concerning preferences.

One of the main challenges in building and room acoustics is to assess, by objective descriptors, the acoustic performance of building structures on one hand and the acoustic comfort in building interior on the other hand. In room acoustics, many parameters that express the perception of loudness, reverberation, speech intelligibility, clarity of sound or spaciousness have been established over the years. In building acoustics, the sound insulation properties of walls, floors and building elements are measured according to international standards (series of ISO 10140) and rated according to (series of ISO 717), the results being expressed as single-number quantities or descriptors being a sum of a single-number quantity and a spectrum adaptation term. A need for revision of requirements for dwellings has increased due to acoustical problems resulting from (1) Increased use of lightweight structures (2) the appearance of new kinds of sound sources in households, with higher sound power, and often also containing strong low frequency components (3) new infrastructures and technical services in buildings that produce more installation noise than before (such as air-conditioning), which are often indicated as very disturbing, not always due to very high sound levels, but because of different tonal components.

Low frequency components in sounds produced by inhabitants of dwellings have uncovered the weak points of recently very popular lightweight constructions. Lightweight walls are typically based on mass-spring-mass systems with typically very high sound insulation values at middle and high frequency ranges, but their modal behaviour below 100

Hz causes the deterioration of sound insulation properties of such building elements (e-book - COST Action FP0702).

The question arises, how to evaluate the airborne and impact sound arising from neighbour activities and how to determine the acceptable limits of disturbance. A simple solution for the first step could in many countries be to enhance the value of sound reduction index for walls and floors between apartments by making the limit value stricter and by proposing to extend the frequency range to lower frequencies. However, research by means of listening tests could be very useful for obtaining a more refined vision on the problem and its possible and optimized solutions as the second step. Besides the problems of acoustic discomfort due to sound sources originating from neighbours, transmission of sound between neighbouring apartments evokes privacy issues as well.

High quality auralization and sound reproduction systems in special laboratory conditions, combined with findings from audiology and psychology enables the researchers to perform a variety of listening tests that can help in the development or validation of proposed methods, for deciding about threshold values on parameters for standards and for constructing guidelines in order to reach the desired acoustic comfort in building interior.

7.2. Perception of sound and its interpretation

7.2.1. Hearing and listening

In acoustic terms, hearing and listening is not the same thing. Hearing is one of the five human senses and can be described as the physical process of perception of sound. The dynamic range of the audible magnitudes of sound of a healthy human ear is around 130 dB and the frequency range between 20 – 20 000 Hz. Listening is a cognitive process of actively sensing and interpreting, involving both behavioural and cognitive activities (Greene, 1988). Sound can also significantly affect our emotions and its perception and interpretation is very complex.

7.2.2. Hearing tests and listening tests

There is also a difference between hearing tests and listening tests. The tests performed by audiologists to evaluate the sensitivity of a person's sense of hearing, belongs to one of the typical hearing tests. Listening tests on the other hand represent the important class of perception tests that are chosen according to the nature of the phenomena to be investigated. Listening tests belong to perceptive measurements where the sound is used as a stimulus. In the field of building and room acoustics, listening tests are essential for the conception, verification and selection of objective acoustical parameters that allow us to assess the acoustical situation in buildings in a quantitative and concise way.

Listening tests may be discriminative (e.g. paired comparison) or descriptive (e.g. semantic differential). In NT Acou 111 (2002-5) two types of listening tests are distinguished: (1) so-called "objective", related to perception of what do the subjects (persons) hear) or (2) so called "subjective (affective)" related to what do the subjects prefer or dislike. In the so-called objective tests, the main purpose is to give information about the character of the sound and in the so-called "affective" tests to give information about people's perceptions of sound in a given context.

7.3. Conception of listening tests

A listening test can be seen as a compilation of 4 phases: One starts from an (1) original sound signal, as it is generated by a natural (vocal sound, sound of river or sound producing object such as hammer or footsteps) or artificial (digital or analogue synthesizer) source. The (2) sound is then propagating through the medium between the source and the listener. The effect hereof is that the initial sound signal is convolved with the impulse response of the surrounding space or environment and the (3) Head-Related Transfer Function (HRTF) of the receiver. The environment can be homogenous and therefore relatively simple (if sound is propagating "only" in air), but can be also more complex, in cases where sound is produced in one room, passing through different kinds of obstacles such as wall or floor structures, to be radiated by these structures in a neighbouring room, creating audible changes in air pressure. In these cases modelling or measuring the sound field in sending and receiving room as well as sound propagation through the material is necessary. HRTF can be measured on a real person or on artificial head and can also be simulated by BEM models. Finally, the sound arriving in a person's ears, is processed by the (4) physical and neurological parts of the hearing system. These phases are all interconnected and cannot be seen in isolation. This process can be based on measurements or on simulation, followed by "auralization" of the arbitrary sound signal. An auralization has to be understood as a process in which measured or simulated sound field is made audible (Vorländer, 2008).

7.4. Measurement based auralization

In order to keep maximum control over the features of sound stimuli to be used in listening tests, it is important to record the initial sound in anechoic and noise-free conditions, and using a microphone and pre-amplifier with a flat or carefully calibrated frequency response over the whole audible range (ideally 10 Hz till 18 kHz, inferring a sampling frequency typically 44.1 kHz), and with a linear response over a wide dynamic range (ideally 0 dB SPL to 120 dB SPL). This is to ensure that the sound is not influenced by unknown room-acoustic, audio-electronic, or unwanted source aspects.

For binaural auralization, the use of the artificial head is essential. For the listening tests, the microphones of the artificial head need to be placed at the ear entrance rather than the eardrum, in order to avoid the multiplication of the ear channel filtering (once in the artificial head during recording and again by the ear channel of the listener himself) during the listening tests. If the measurements are done by microphones placed at the eardrum, the ear channel influence can still be compensated for, as well as the frequency response of the headphones.

Measurement based auralization in building and room acoustics is accurate, but doesn't allow enough flexibility to perform parameter studies where the influence of a specific feature could be easily and systematically investigated (Jeon et al 2004). Development of the simulation models is therefore of main interest when research studies are going to be based on laboratory listening tests.

7.5. Prediction models and auralization

In room acoustics, sound propagates in only one medium, i.e. air, which makes prediction somewhat easier in comparison with building acoustics. A partial overview of the state-of-the-art achievements in auralization used in room acoustics is given in (Rindel 2004; Vorländer 2006; Rychtarikova 2011).

In building acoustic application, more calculations are involved, since the simulation model requires modelling of the sound field in both sending and receiving room, as well as of the sound propagation through the material of the construction separating both rooms. Distinction is also made between airborne sound, impact sound, and sound from installations. Prediction models developed by (Vorländer 2006) have shown sufficient accuracy in 1/3 octave band spectrum useful for research on ratings of sound insulation. The proposed method has been proven to be satisfactory for auralization purposes as well and can be used for investigation of the sound effects, noise and noise annoyance by variations of constructions, via listening tests.

Another approach to this topic is simplified energy-based approach proposed in Odeon or RAVEN software, for example. The separation wall between the 3D modelled rooms is characterised by frequency dependent sound reduction index in one-third octave bands (Fig. 7.1). Simulations are based on particle tracking and its result is an impulse response that also allows auralization (Rindel 2008). In this energy-based method standing waves and other acoustical effects that relate to wavelength won't be detectible but it seems that under certain conditions, this method can be used for the rough estimations (Ronasi 2003).

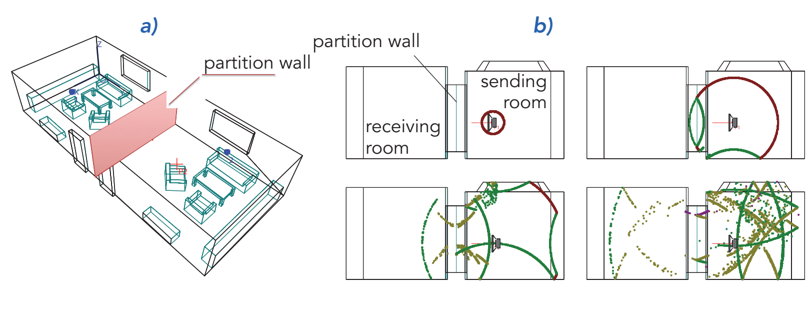

Figure 7.1. *Illustration of the sound transmission calculation by using particle based method in Odeon software a) STSM-TU0901-9967; b) STSM–TU090–6953.*

Ray-based software offers possibility to work with surface sources (partition between two rooms or a floor) that have a frequency spectrum corresponding with the neighbour's sound filtered by the construction. This approach has been used for the assessment of foot-fall noise, including localization of the source (Brunskog et al 2009) and in the framework of proposal for a "living spectrum" in single number rated airborne sound transmission (STSM•TU0901•6953).

7.6. Stimuli and its presentation

Stimuli in listening tests are sound samples used in the listening experiments. In all phases the stimuli can be regarded 'in time domain', as sound pressure as a function of time. When only one isolated feature is examined in the experiment (e.g. test on loudness, pitch, angle of the arriving sound perception), it is called a 1D stimulus. When more than one feature is followed in one experiment, then the stimuli are referred to as multidimensional. In laboratory listening tests, the presentation of the stimuli can be performed by a variety of sound reproduction systems depending on the origin and type of stimuli. The two most common approaches for the presentation are (1) multi-channel loudspeaker systems that reproduce multi-channel recordings or sounds obtained from simulations, while the second approach is (2) headphone presentations. In order to avoid unrealistic reproduction, the influence of the reproduction system itself has to be considered already when preparing the stimuli. Loudspeaker systems allow the subjects to listen in a natural way, with their own ears, but the signals and the distribution of the loudspeakers must be very well balanced and so-called cross-talk cancellation filters that are based on the HRTF need to be used for virtual auditory space synthesis (Akeroyd et al, 2007). Ambisonics represents a feasible spatial sound reproduction technique based on spherical harmonics (Pelzer et al 2011).

When using headphones, front-back confusion can be a problem, due to subtle inaccuracies of the HRTF information related to not properly modelled spatial filtering effect of the pinna. However, the localization in frontal horizontal plane will be affected only minimally. In listening tests for building acoustics, binaural and monaural cues are less crucial than in audiological research. However, to be able to present stimuli in the most realistic way, all recommendations for loudspeaker and headphone presentation systems need to be taken into account.

7.6.1. Visual feedback

Visual stimuli can influence our perception of auditory stimuli. E.g. seeing a speaker in an otherwise empty room already suggests that sounds in that room are originating from that speaker and not from somewhere else. Showing different pictures of nature will influence pleasantness of perceived sound and vice versa. In listening tests, it is therefore important to choose a proper visual surrounding, which should be the same for all listening subjects, and to decide if visual feedback will be given at all. In order to eliminate experimental uncertainty in a listening test, it is important that all subjects undergo the same experimental procedures, considering both auditory and visual conditions.

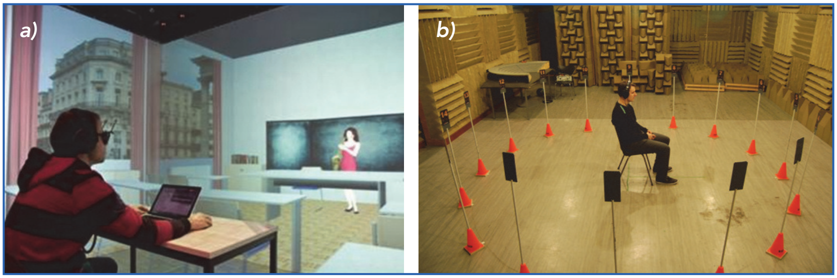

Figure 7.2. a) Virtual Reality Center at RWTH Aachen University; b) anechoic room at KU Leuven during the headphone experiment on sound localization.

7.7. Recommendations for listening tests related to sound insulation assessment (proposal of COST TU0901 WG2)

7.7.1. Accuracy levels

The quality and reliability of listening tests (for the assessment of sound insulation) is extremely sensitive to (i) sound levels of reproduced stimuli, (ii) frequency response of the reproduction system (such as headphones) and (iii) the environment in which the listening test is performed. It is not always possible or necessary to fulfil the highest quality of stimuli presentation. Therefore three accuracy levels are defined: (1) Demonstration purposes (Level 1), (2) Survey-type applications (Level 2: level calibration, silent environment), (3) Research purposes (Level 3: level and frequency calibration, sound proofed laboratory)

(1) Demonstrations are in general likely to be made for the representatives of the decision-making government entities, other experts in the related interdisciplinary fields and/or the general public. Level 1, accuracy is required for demonstration purposes. More specifically, it is not necessary to keep the levels of the output sound samples at realistic values, nor is the frequency response compensation of the reproduction system required. Given that such demonstrations will be held in readily available and not necessarily laboratory spaces, it is allowable/advisable to raise the levels of reproduced sound samples to account for the presence of presumably high-level background noise in such spaces. Given the overall listening conditions in such spaces, the frequency response compensation is not of primary concern. To achieve portability, headphone reproduction is preferred over loudspeakers.

(2) Survey-type applications would include e.g. subjective evaluation of sound-insulation properties of new or existing materials or building

constructions, in particular in the development process. In that light, level 2 accuracy is demanded, meaning that it is important to maintain realistic levels of output sound samples, even if this means that some of them will not be heard. As a consequence, a noise-free (or at least a low-noise environment, with limited usability) environment is required for performing such surveys. For survey purposes, the frequency response compensation of the reproduction system is optional, but not imperative.

(3) Research applications require level 3 accuracy as important decisions might be taken based on research results. Typical research questions include e.g. the determination of the relationships between loudness of perceived neighbour noise and objective sound insulation measures. This means that it is imperative to apply both level calibration and frequency response compensation. A noise-free laboratory environment is required, with properties described below. Background noise level at each 1/3 octave band must be at least 10 dB lower then sound level of the most silent stimulus, in order to avoid masking effects.

7.7.2. Sound samples description and collection

The core type of stimuli, i.e. source sound samples of interest, is formed around the typical sounds found in daily life, originating from neighbouring dwellings, but also within a dwelling itself, such as speech, music, typical kitchen and bathroom sounds, sounds made by children, party sounds, etc. As sound can originate from outdoors as well, traffic noise is also regarded as an interesting sound to be used in subjective testing. In suburban or rural areas, a significant contribution to the overall sound environment is given by various kinds of outdoor equipment and/or power tools, which makes them worth involving into the investigation as well.

7.7.3. Input files, recording conditions and equipment

Although the reverberation present in the source sound is not critical for sound insulation studies, the general consensus is that source samples should be recorded in anechoic conditions if available. If not, recordings should be made in ordinary rooms in the near field of the source, with the reverberation time in the room not longer than 0.4 seconds. Reverberation in source sound characterized by reverberation time longer than the stated value may be tolerated, but only for presentation/demonstration purposes, while such sound samples should be avoided in the preparation of final test sounds. Objective measures such as equivalent sound pressure level L_{Aeq}, L_{Ceq} or L_{Zeq} should be listed, along with 1/3-octave band spectrum. If possible, loudness parameters should be calculated as well. To describe and/or evaluate the temporal structure of the sounds, statistical parameters such as L_1 and L_{10} should be calculated.

Measuring and recording distance from the source should be set at 1 m, with any deviations clearly stated and the reasons for making them explained. To make the level calibration easier, a 1 kHz calibration tone of a known level should be included into the recording, obtained from a calibration device.

Recording setup should be clearly stated. Mono and stereo recordings are preferred, at the sampling frequency of no less than 44.1 kHz and at least 16-bit resolution. Assuming that the recorded sounds will undergo signal processing, it is recommended to use higher sampling frequencies of 88.2 or 96 kHz, and higher resolutions of 24 or preferably 32 bits, which also provides higher signal-to-noise ratio. After signal processing, the finalized sound samples can be downsampled/converted to lower values of the sampling frequency and/or resolution, if so required by the reproduction method. Only audio formats with no compression must be used, e.g. the .wav format or similar. Audio formats that utilize lossy compression, such as MP3, must be avoided at all costs due to audible compression artefacts. Their use can be tolerated in exceptional cases, for demonstration purposes only. In case of a stereo recording, the recording technique (coincident, near-coincident, or spaced) and specific microphone setup (ORTF, NOS, Blumlein, M/S, etc.) should be noted. Photographs of the recording setup are advantageous.

7.7.4. Output files, reproduction/ playback system

If headphones are used, output sound samples should preferably be binaural in order to avoid in-head localization. Open design headphones are preferred, as closed ones change low-frequency response depending on the "goodness-of-fit" to the listener's head, making the frequency response compensation difficult. On the other hand, closed design provides a certain amount of sound insulation, thereby reducing the background noise perceived by the listener, and making the demands on the listening room and its background noise a bit looser. For demonstration purposes, closed headphone design is a logical choice. (Semi)-open headphones, on the other hand, offer exactly the opposite, in other words, almost no sound insulation from the environment, but easier frequency response compensation, as the fitting to the listener's head is not critical for low-frequency response. These properties make the (semi)-

open design ideal for survey and research applications. The drawback of binaural headphone reproduction is the lack of full 3D directional information, specifically, height information, assuming that such kind of reproduction is desired and/or required. The sound samples must be presented on exact relative levels in all accuracy levels (no matter if the files are reproduced at realistic or raised levels). Frequency response compensation (if required) should be easy to implement via 1/3-octave band equalizer, in the stimuli preparation stage. Compensation data will be available for known headphone models.

If loudspeakers are used for reproduction of sounds, the output file can consist of 1 up to N channels, where N is the number of loudspeakers. If necessary, reverberation can be added to convolved source recordings in order to simulate realistic receiving room conditions, which is especially suitable for loudspeaker-based reproduction, in which each channel can represent an individual flanking path.

The use of a loudspeaker system, ranging from a single loudspeaker intended for mono reproduction up to an N-channel system designed to offer full 3D spatial information and listener envelopment typical for real-life situations can be convenient and suitable for reproduction, in which each channel can represent an individual flanking path. Both Vector-Base Amplitude Panning and Ambisonics are viable choices. Given that it is not necessary to achieve precise localization, but only to give a hint on the general direction the sound is coming from, the size of the system, i.e. the number of loudspeakers can be kept reasonably low ($N \leq 16$ is sufficient in most cases). On the other hand, the increase of the number of loudspeakers stabilizes the sound image, thereby offering the possibility to have more than one listener at a time, provided that the listening room itself is large enough. As a disadvantage of loudspeaker reproduction, each of them inherently introduces additional broadband noise (the amount being dependant on loudspeaker manufacturing quality) into the laboratory space, which then sums up at the listener position, raising the overall background noise profile. The demands on background noise in case of loudspeaker reproduction are even stricter than in case of headphone reproduction.

The use of high-quality components in the entire reproduction chain is imperative, in order to maintain a flat frequency response and keep the background noise level as low as possible. In that sense, built-in sound cards must be avoided; external USB, IEEE1394 or other types of audio interfaces have to be used.

7.7.5. Demands on laboratory for research purposes

For demonstration purposes, the choice of room intended for presentations should be based primarily on the level of background noise. Survey and research applications demand that background noise level is kept as low as possible, desirably at least 10 dB below perceivable limits, if the sound samples are to be played at realistic levels. Higher background noise levels severely disturb both loudspeaker and headphone reproduction based experiment, posing as a limit to the maximum sound insulation that can be presented in such a laboratory. The issue of background noise originating from both outside and within the laboratory must be addressed, the former by ensuring proper sound insulation of the laboratory building itself, and the latter by removing all potential noise sources from the laboratory, other than the ones absolutely necessary for the conduction of specific tests. Equipment such as data projectors, computers, must be placed outside the listening test room. Besides auditory disturbance caused by background noise, no activity that would visually disturb the listeners should be allowed in the laboratory. In that light and having in mind the sensitivity of these tests, i.e. the low-level of the test sounds, it is advisable to perform the test having only one listener at a time, so that multiple listeners would not disturb each other during the test. For loudspeaker-based reproduction, the reverberation in laboratory space has to be kept as low as possible by implementing proper acoustic treatment. If necessary, the reverberation can be added in the stimuli preparation stage in order to simulate normal room conditions, rather than inherently having it in the laboratory space. For headphone reproduction it is also advisable to treat the laboratory acoustically, thereby additionally reducing the level of background noise in the laboratory, thereby additionally reducing the level of background noise in the laboratory. By doing so, the audibility of background noise created by the listening person (caused by movements, breathing…) will also be reduced.

In order to understand the limits asserted by the presence of background noise and to be able to utilize a given space to those limits, it is not sufficient to arbitrarily set the level difference between the reproduced test sound and the present background noise. Both spectral and temporal profiles of background noise in the laboratory have to be recorded. The same basic data as already listed for source files must be given (L_{eq}, 1/3-octave spectrum, statistical parameters). By comparing the spectrum of the test sound with the spectrum of recorded background noise the minimum level of test sound can be determined, assuming that the level of test sound must exceed or at least be equal to the level of background noise in each individual 1/3-octave band. From this data, maximum presentable sound insulation can be determined, having in mind the realistic level of the source and its spectrum, as recorded in the stimuli preparation stage. In general, steady broadband background noise proves to be the easiest to deal with. Time-varying noise and/or the presence of tonal components results in further penalization reflected in required additional increase of the level of test sound.

7.7.6. Subjects (test persons, listeners)

A subject is a person participating on the perception experiment. We distinguish between naïve listener and expert listener. Naïve listener (assessor) is a person who does not have any expertise or knowledge in relation to the test. Expert listener is a person who has knowledge or experience in the investigated field and is competent to give his/her opinion.

The subjects could either represent the entire population, taking into account gender, age and other relevant factors, or be chosen from a pool of young people with, presumably, normal hearing. The question remains whether the hearing of young people is indeed normal and it would be advisable to record the audiogram of each and every listener that takes part in a listening test. In order to perform a meaningful statistical analysis of the results obtained from a test, a minimum number of 30 listeners should take part in such a test.

7.7.7. Psychoacoustic methods (tasks of subjects)

The WG2 of COST TU0901 doesn't prescribe any particular psychoacoustic measuring method, because the choice of a method depends on a type of experiment. However, the most popular methods used in assessment of sound insulation are so far paired comparison test and semantic differential tests and direct ratings in visual analogue scales (VAS).

In pair comparisons, stimuli A and B are compared in pairs. The number of comparisons can be calculated as n(n-1), where n is the number of sounds. Pauses between the sound samples are typically around 1 s. The advantage of paired comparison is, that it gives the listeners the ability to detect small differences in different sounds. The information obtained from such a test is typically of the type "louder/ more silent" or "higher/

lower” without information about the absolute feature of the sounds. In pair comparisons, sound samples are typically between 2-7sec.

The semantic differential gives an assessment of sound by words without comparison with other sounds. Because no direct comparison is intended, pauses between sound samples are recommended to be 10 seconds. The duration of the sounds is typically longer than sound samples for paired comparison tests. If numeric scales are used, e.g. seven- or nine-point scales are recommended (NT ACOU 111). If interval scales are to be used as a basis for specific statistical analysis methods, instruction should be given to test persons to understand and use them as such.

In any tests, it is highly recommended to randomize sound samples so, that no subject would have sounds presented in the same order as the others.

All test persons should get the same explanation about the experiments, preferably written in the form of a short and clear instruction with indication that the test doesn’t contain right or wrong answers, but simply goes on subjective perception. Results from tests should be analyzed by statistical analysis (Montgomery 2001; Cohen 1988; Stone&Sidel 1993) in order to indicate relevances and statistical significances.

The tasks that fall within the scope of the listening tests related to subjective evaluation of sound insulation range from demonstration, through survey up to research activities. The research, being the most sensitive part of the three, should focus on determining the relationship between loudness (or annoyance / disturbance / satisfaction) of perceived sound and objective measures that describe the sound insulation properties of building constructions. In that sense, annoyance can also be related to the loudness of the sound in the receiving room, i.e. the one that remains after passing through a wall, a floor or another building construction put under test.

However, a common problem associated with annoyance evaluation is that the laboratory conditions are not at all similar to the usual living conditions, resulting in an out-of-context evaluation not suitable for assessing annoyance. Moreover, the exposure to a sound during a laboratory test is in most cases too short to yield a valid response that would indicate a true degree of annoyance. To overcome these issues, a possible solution is to perform rank tests related to annoyance estimation, rather than insisting on annoyance assessment using an absolute scale.

If complex psychoacoustical percepts are to be addressed, such as annoyance or disturbance, it is very important to define a clear context in which the evaluation should be made. This will help in the interpretation and comparisons of the results obtained in different laboratories. Nevertheless, annoyance or disturbance evaluations (as well as other complex psychoacoustic percepts) derived in laboratory experiments should not be directly compared with annoyance or disturbance ratings derived from socio-acoustical surveys, due to the inherent difference in their elicitation.

In any case, if repeatability of the results is to be achieved for different laboratories, round-robin testing is highly advisable in order to verify or dispute such results and to find additional guidelines for possible improvement.

7.7.8. The importance of listening tests to assess contextual and cultural aspects in sound perception

Psychology plays a large role in the perception and judgement of soundscapes. The sound we produce ourselves in our own apartment (TV, music, cooking, taking shower or talking) have much higher sound levels and often also an objectively much more annoying character (vacuum cleaner or drilling machine) than the sound produced by neighbours. Nevertheless, we very seldom complain about the noise we produce ourselves, while complaints about neighbour noise are quite common.

Irrespective of the objective descriptors, the nature of the activity responsible for the sound produced by neighbours has a large influence on a listener's feeling of annoyance. Finally, the physical and mental activity of the listener himself or herself is a determining factor for his/her assessment of the soundscape, e.g. pleasantness/annoyance of sound. In order to get insight in these factors in combination with the objective parameters, carefully performed listening tests with well controlled variation of relevant parameters represent a valuable tool.

7.8. Research studies performed in the framework of WG2

In the framework of COST TU0901 several studies have been conducted on the subjective assessment of airborne sound insulation in dwellings.

In the research of Horvat et al (2012a) performed during his STSM stay at ITA Aachen and partly at his home institution as well, an examination of required signal-to-noise margin in laboratory subjective evaluation of sound insulation has been performed. The importance of having a noise-free laboratory environment is crucial, if subjective evaluation of sound insulation is to be performed.

Horvat et al (2012b) investigated the suitability of 3D sound reproduction and the influence of background noise on subjective assessment of sound Insulation. Common spatial audio reproduction techniques, namely Ambisonics, Vector-Based Amplitude Panning and Cross-Talk Cancellation were examined, and their potential for use in the listening tests focused on subjective evaluation of sound insulation was evaluated, and the advantages and disadvantaged of each technique were discussed regarding this specific application.

Pedersen et al (2012) have performed a feasibility study on online listening tests on sound insulation of walls. Their listening test was made on the annoyance potential of airborne noise from neighbours heard through walls. 22 assessors from 11 countries rated six simulated walls with four types of neighbour noise online at the assessor's premises using the ISO/TS 15666 annoyance scale. A simple "calibration" procedure based on adjusting a speech sample to natural level for approximate calibration was used.

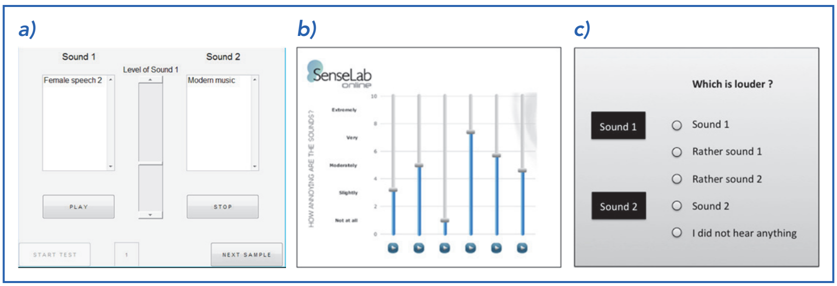

Figure 7.3. *Illustration of the users interface as used in the experiments of a) Horvat et al 2012a; b) Pedersen et al 2012; c) Rychtarikova et al 2013b.*

The preliminary study of Rychtarikova et al (2012a) concerns perceptual comparison of the sound transmitted through two different walls: (1) a light-weight wall and (2) a masonry wall. The two chosen walls had different (laboratory measured) sound insulation spectra R, but the same single value rating R_{living} = 51 dB. In spite of their equal R_{living} ratings, significant differences in subjective acoustic insulation performance between the walls are found and therefore it rises the question if the proposed "living noise rating" is the most adequate rating spectrum when considering correlation to perception.

In the study of Ordoñez et al (2013) a façade insulation of 10 different construction types was subjectively evaluated using three psychoacoustic methods: paired comparisons using a two alternative forced choice (2-AFC) paradigm, direct scaling using a visual analogue scale (VAS) of individual stimuli and direct scaling using VAS of five stimuli at once The stimuli used in the evaluations were obtained by filtering recordings of traffic noise with the frequency response of sound insulation measurements. The measurements were performed in typical Italian buildings in accordance with the ISO 140-5 standard. The objectives were to compare subjective sound insulation quality obtained with the three psychoacoustic methods, and to investigate the correlation between the subjective assessments and objective ratings of different construction types.

Hongisto et al (2013a) show preliminary results of a laboratory experiment on disturbance caused by airborne living sounds heard through walls. The aim was to determine the correlation between the most typical single-number quantities (SNQ) of airborne sound reduction index and perceived disturbance in domestic context. Special care was taken to design the experiment so that different living sounds, realistic sound levels and a wide spread of typical party walls were used. The focus was within 50 and 5000 Hz. 26 subjects participated in the experiment. Each participant evaluated the disturbance of 54 sounds while imagining that they were at home relaxing and reading a magazine. Based on this study, it seems that other well-known SNQs, like R_{speech} and R_w, can also be primarily considered because they predict disturbance slightly better than R_{living}.

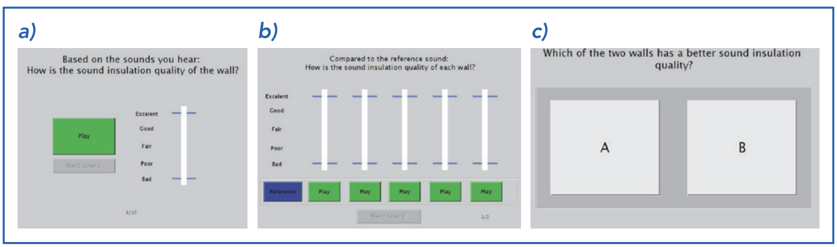

Figure 7.4. *The users interface in the experiment of Ordoñez et al (2013). The user interfaces: a) direct scaling of single stimuli; b) direct scaling of five stimuli; c) paired comparison.*

In the research performed by Hongisto et al (2013b) the main research questions are related to "How standardized single-number ratings of airborne sound insulation predict subjective perception of various living sounds"? In this study, fifty-nine subjects participated in the experiment. Each participant evaluated the disturbance of 54 sounds while imagining that they were at home relaxing and reading a magazine. Six spectrally different living sound types were examined. It seems that the disturbance is predicted relatively well by SNQs focusing on the frequency band 100-3150 Hz.

Thorsson (2013) conducted laboratory listening tests on footfall sounds. Based on the literature study a listening test methodology has been devised that one can use with measured data from field situations. The recorded acceleration signals were reproduced using ceiling-mounted loudspeakers and subwoofers. The reproduction system was designed to reproduce signals down to 16 Hz and the reproduction level was measured to be equal to footsteps on the real floor. The listening test was done using pairwise comparisons between one sound with fixed level and one sound where the subject could vary the reproduction level. Two questions were used in the tests: 1) adjust the sounds to equal annoyance, and 2) adjust the sounds to equal loudness. Different objective measures for evaluating the footstep sounds were tried using the residual between the mean subjective score and the value of the objective measure as error marker. The minimum residual sum of all listening test comparisons was the average A-weighted maximum level.

The article of Rychtarikova et al (2013) presents the effect of temporal and spectral features of the presented stimuli on loudness perception. In their study, 15 different stimuli with duration of 5 seconds were presented to subjects via headphones in three ways: (1) original daily life signals, auralized as they would sound as after being transmitted through the wall between neighbouring apartments, (2) the time inverted version of the signals in (1) and (3) noise stimuli filtered such that they had the same spectrum as the signals in (1), but without the amplitude modulations (i.e. resulting in a stationary signal). The goal of comparing (3) with (1) was to assess the influence of amplitude modulations on the loudness perception of transmitted sounds.

Although not in the framework of COST TU0901 an interesting overview about the procedures in listening tests in science and industrial praxis has been published in a framework of DEGA, edited by Hellbrück et al (2008).

7.9. Conclusion

The perception of sound is a complex process, since it involves not only objective but also subjective factors. In order to gain insight in this process, it is not only important to accurately determine room acoustical, building acoustical and psychoacoustic parameters, but also to evaluate their relevance and appropriateness for different acoustical scenarios, and, where necessary, to conceive new measures and criteria for judgement of acoustical scenes. Provided they are carefully designed, listening tests performed *in situ* and in laboratory conditions offer an indispensable tool in acoustical research and development of acoustical tools, since they compile all relevant aspects mentioned above, thus strengthening the validity of conclusions and the reliability of resulting acoustic qualifiers.

Development and advancing research in high quality auralization (measurement and simulation based) remains one of the most important research topics for future. Simulations of not only airborne transmission but also flanking and impact noise transmission should be addressed in new research proposals.

More investigation should also be done, comparing different psychoacoustic methods that can be used for validation of a variety of acoustic parameters. Here collaboration with psychologists and audiologist is essential.

A round robin test on listening tests would be a great opportunity to test the uncertainties related to different laboratories and reproduction systems and their impact on listening test results.

7.10. References

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